Incorporating the effects of anthropogenic manipulation of the water cycle in macroscale hydrologic modeling

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for presentation at

workshop on

Satellite Observations of the Global Water Cycle
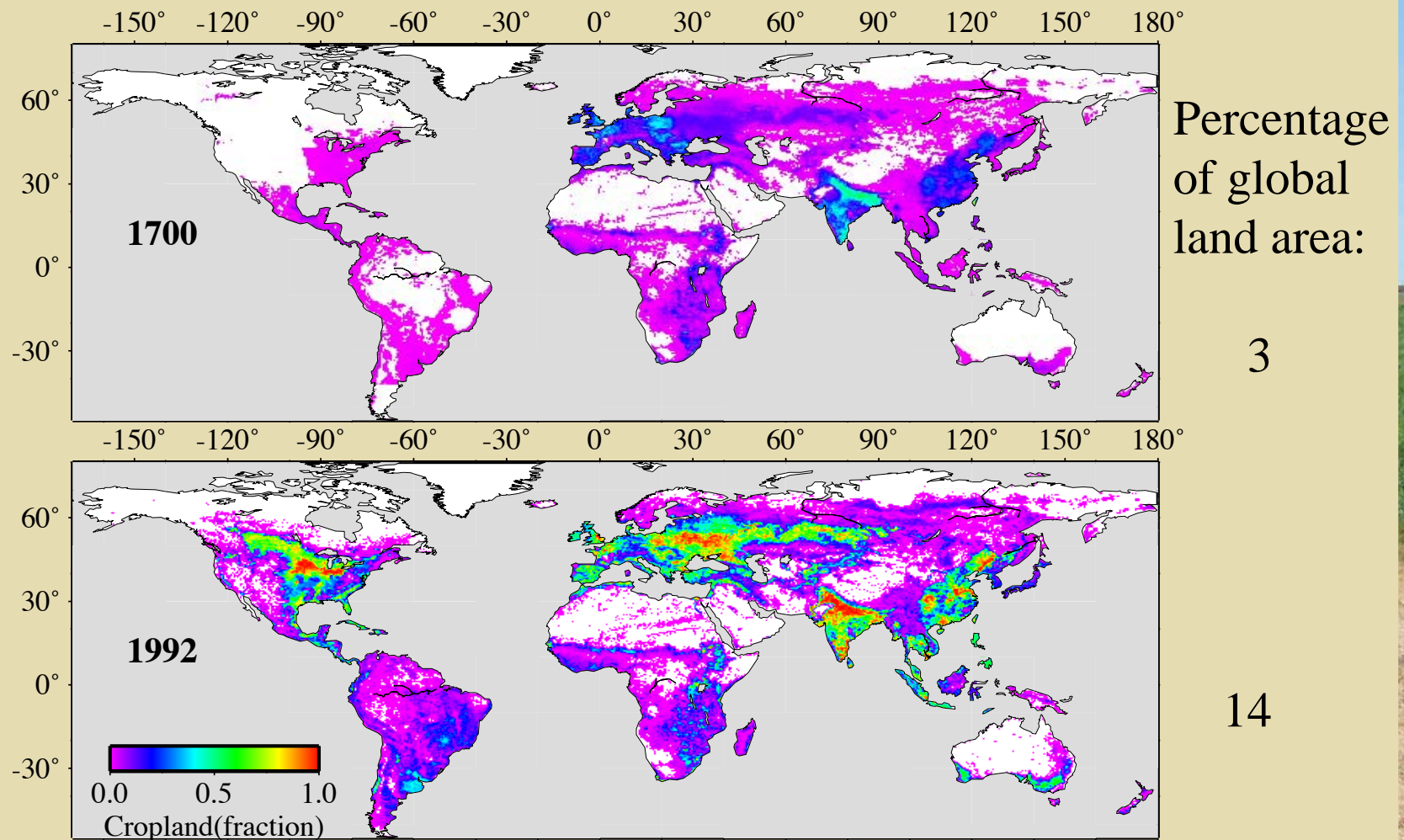
Irvine, CA

March 9, 2007

Basic premise

- Humans have greatly affected the land surface water cycle through
  - Land cover change
  - Water management
  - Climate change
- While climate change has received the most attention, other change agents may well be more significant

Background: Cropland expansion

Percentage of global land area:

3

14

Ramankutty and Foley, *Global Biogeochem. Cycles*, 1999

Background: Irrigated areas
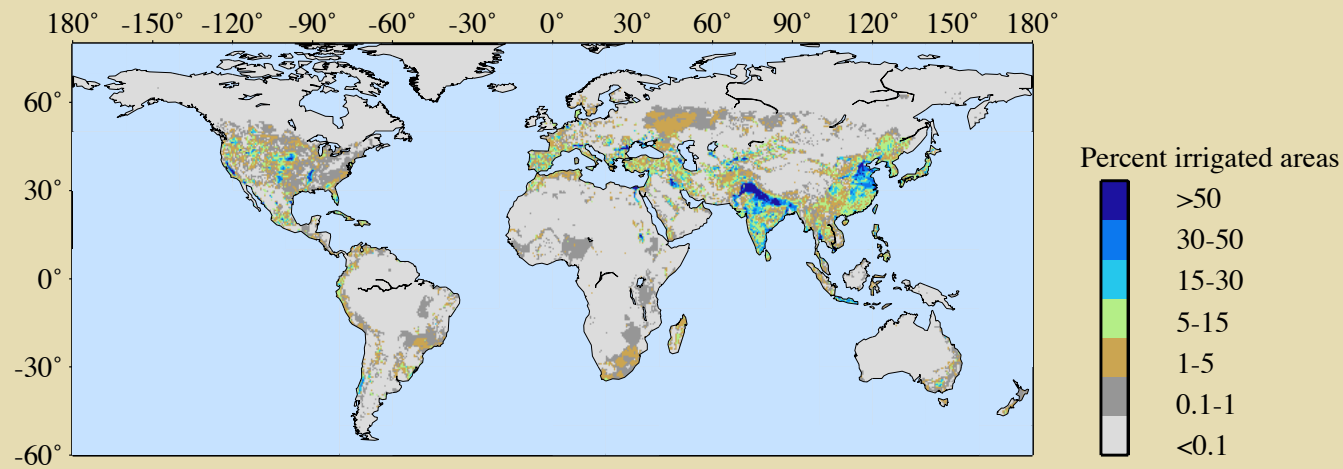
Siebert et al., 2005, Global map of irrigated areas version 3, Institute of Physical Geography, University of Frankfurt, Germany / Food and Agriculture Organization of the United Nations, Rome, Italy

- Irrigated areas, globally:
  - $2.8*10^6$ km^2
  - 2% of global land area
- Location of irrigated areas:
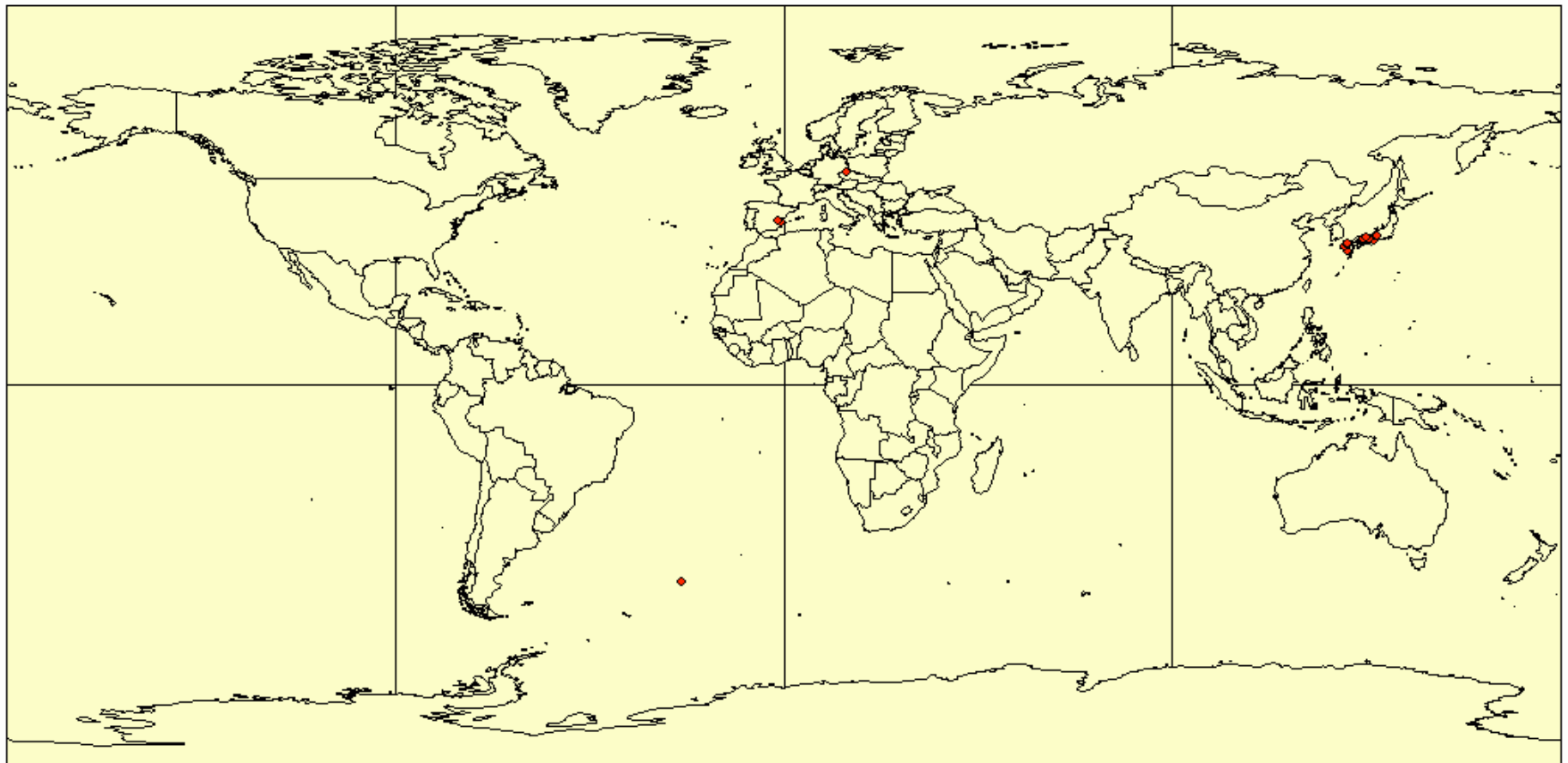 - Asia: 68%
  - America: 16%
  - China, India, USA: 47%

- Irrigation: 60-70 % of global water withdrawals *(Shiklomanov, 1997)*

Global Reservoir Database

Location (lat./lon.), Storage capacity, Area of water surface,
Purpose of dam, Year of construction, …

〜1750年

13,382dams,
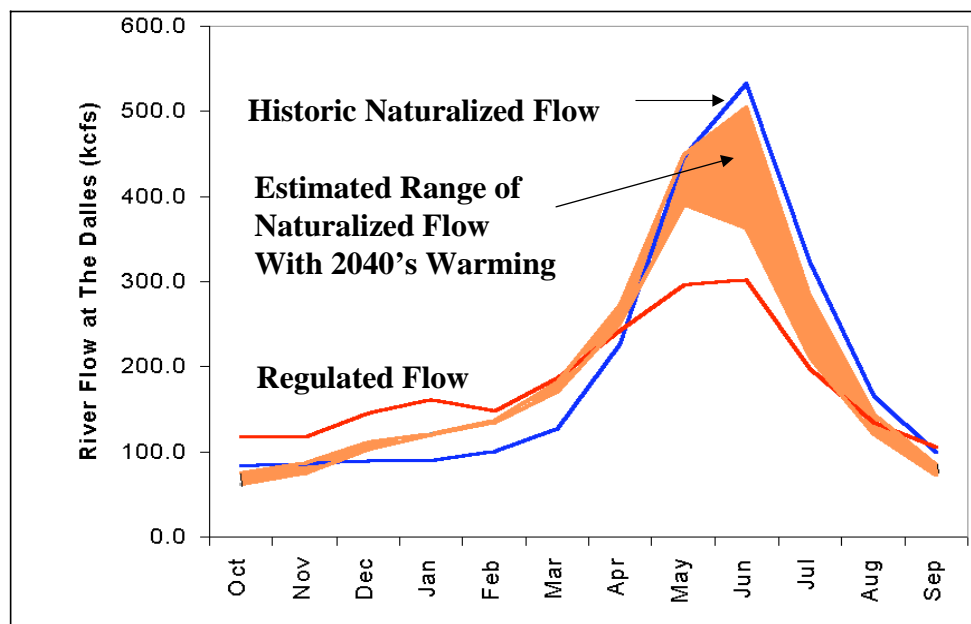

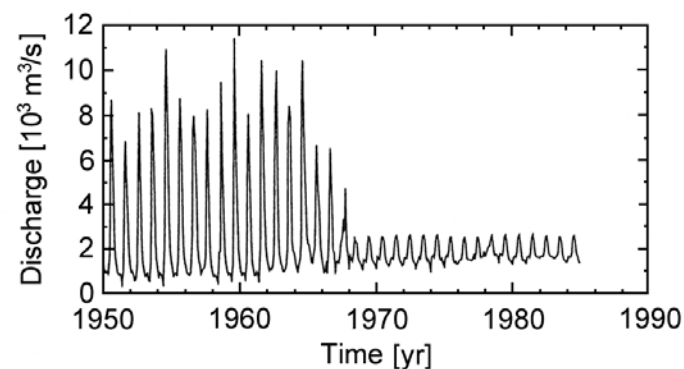Visual courtesy of Kuni Takeuchi

Global Water System Project
IGBP – IHDP – WCRP - Diversitas

Human modification
of hydrological systems

Nile River at the Aswan Dam
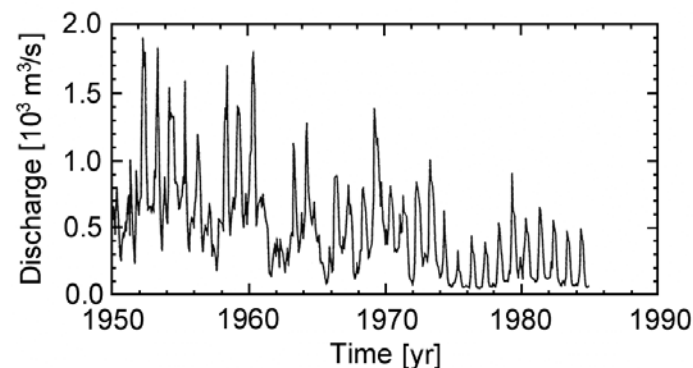
a

Syr-Darya River at Tyumen Aryk

b

Columbia River at the Dalles, OR

Historic Naturalized Flow

Estimated Range of
Naturalized Flow
With 2040's Warming

Regulated Flow

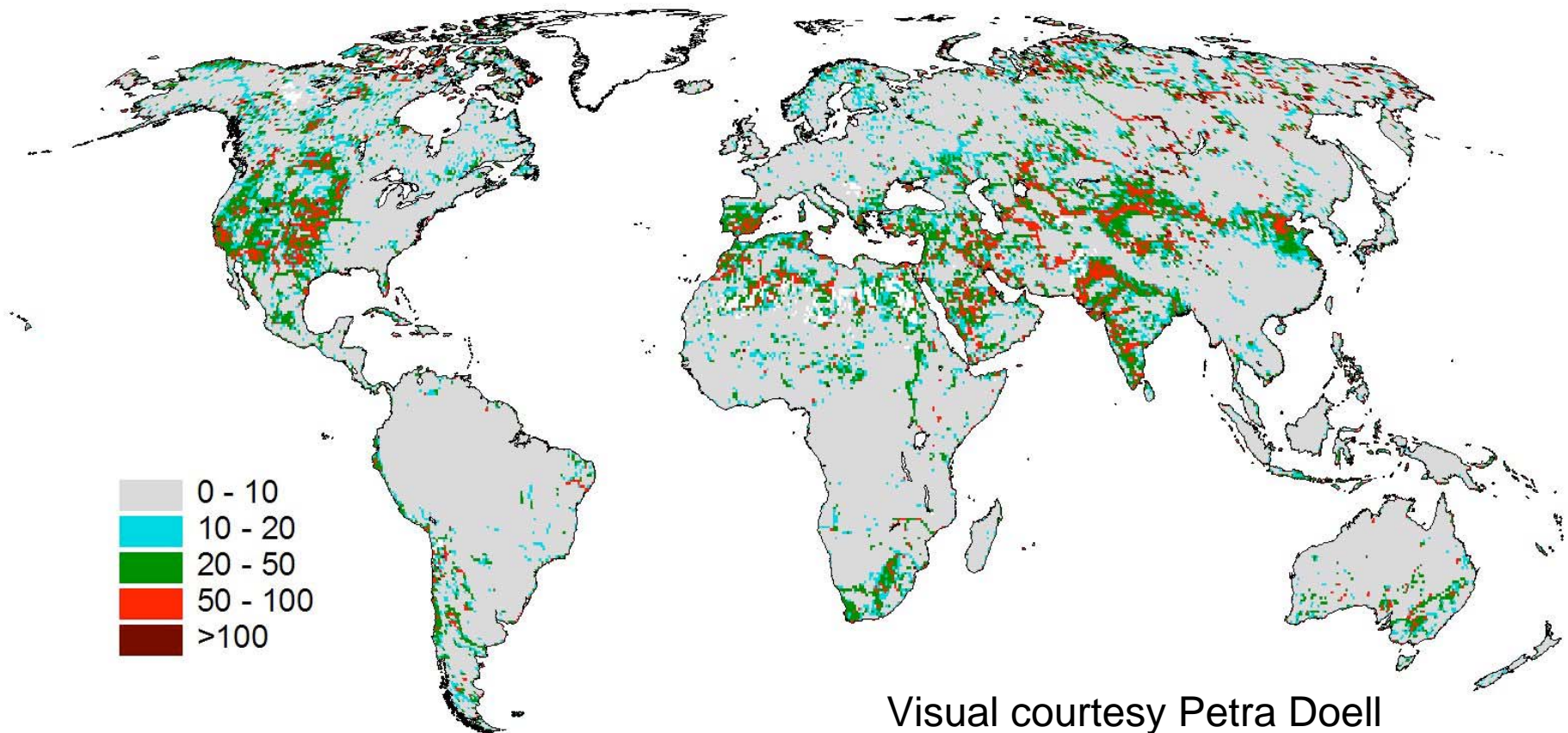**Burntwood River near Thomson**
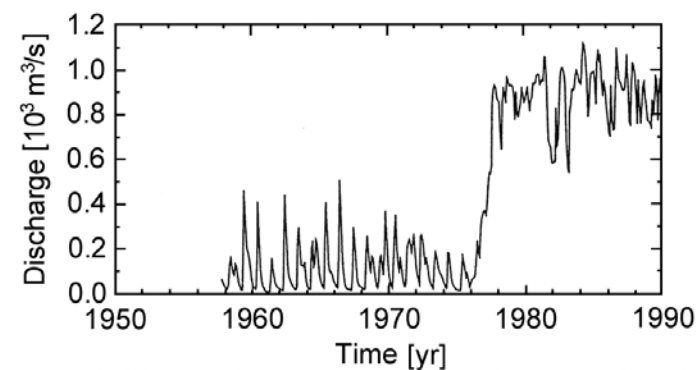
c

Alteration of river flow regimes due to withdrawals and reservoirs

WaterGAP analysis based on "Range of Variability" approach of Richter et al. (1997)

Change in seasonal regime
Average absolute difference between 1961-1990 **mean monthly river discharge** under natural and anthropogenically altered conditions, in %

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Legend:
- 0 - 10
- 10 - 20
- 20 - 50
- 50 - 100
- >100

Visual courtesy Petra Doell

So does it make sense to model the continental water cycle without including anthropogenic influences?

- From the standpoint of global climate modeling (which has been the focus of much of the activity in land surface modeling, maybe (there's lots of ocean out there, global signal probably modest)
- From the standpoint of the land surface (where people live), probably not
- While there have been many studies of vegetation effects (on climate and the water cycle, land surface models are only beginning to be able to represent the effects of water management
- And are the observations (globally or continentally) up to the task?

Some preliminary results from an extension to the VIC construct to represent reservoirs and irrigation withdrawals

for details:

Haddeland et al, GRL, 2006 (reservoir model)

Haddeland et al, JOH, 2006 (irrigation model and evaluation for Colorado and Mekong Rivers)

Haddeland et al, HESS-D, 2007 (vegetation change effects on hydrology of N America and Eurasia, 1700-1992)

For reservoirs – most management agencies (e.g., USBR, COE) have management models that simulate reservoir operations
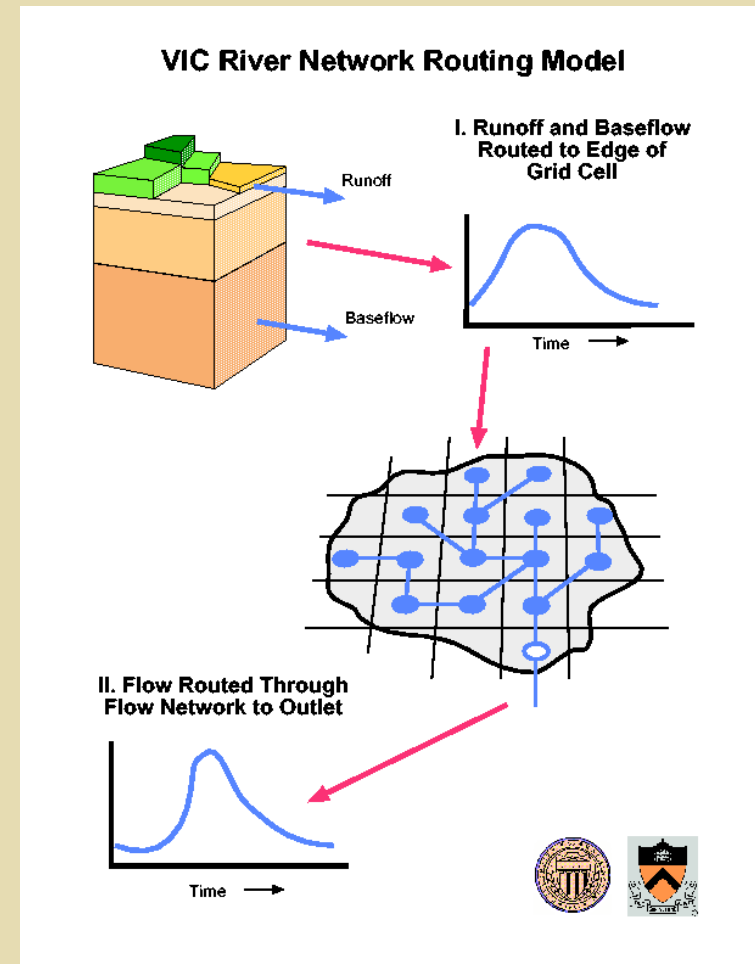
- Models assume knowledge of a) reservoir inflows, b) physical characteristics (active storage, storage-stage relationships), c) operating rules (given storage, inflows, and external factors, what are releases)
- Journals are filled with description of simulation models, and more sophisticated optimization models (dating to 1960s)
- On a global scale, the challenge is to predict reservoir operation given cursory knowledge of reservoir physical characteristics and operating purposes (e.g. flood control, water supply, hydropower)
- Even when local information is available, model errors often result because operating rules are changed (see following slides)
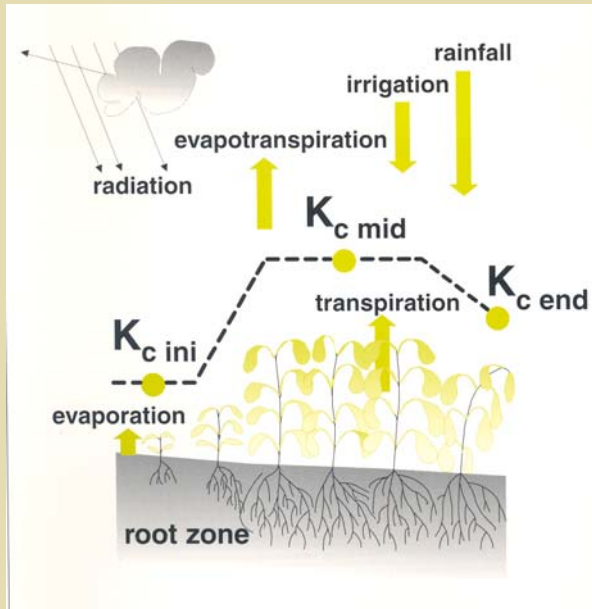
(a) **Total Basin Reservoir Storage**

(b) **Total Basin Monthly Hydropower Production**
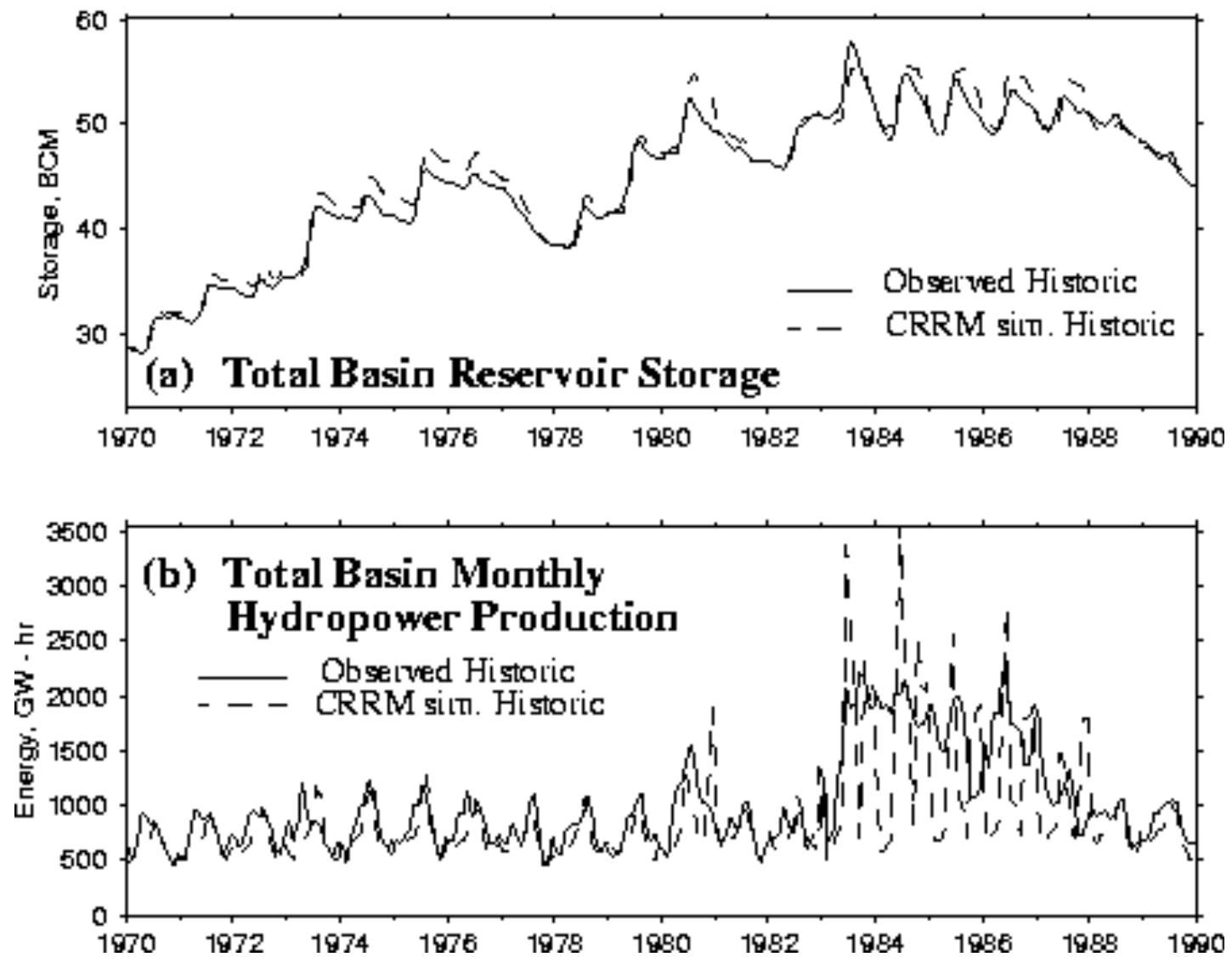
from Christensen et al, 2004

Approach

- **Macroscale hydrologic model**
  - VIC

- **Model development**
  - Irrigation scheme: VIC. Surface water withdrawals only
  - Reservoir module: Routing model

- **Model runs:**
  - With and without irrigation and reservoirs
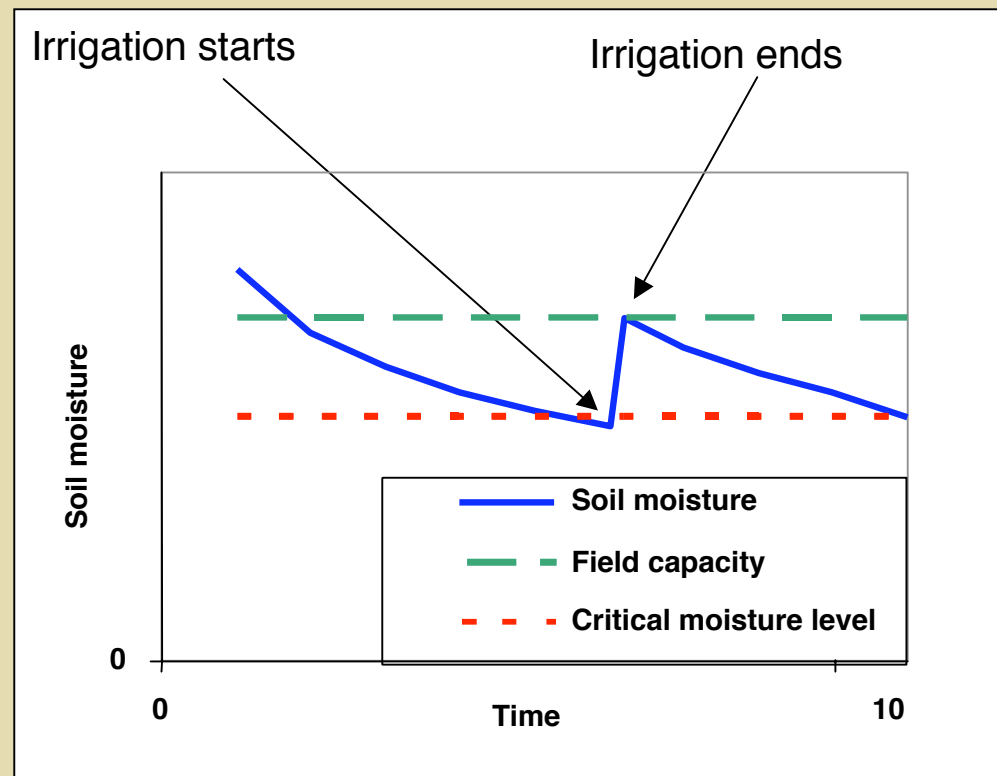 - Historical vegetation

VIC River Network Routing Model

I. Runoff and Baseflow Routed to Edge of Grid Cell

Runoff

Baseflow

Time

II. Flow Routed Through Flow Network to Outlet
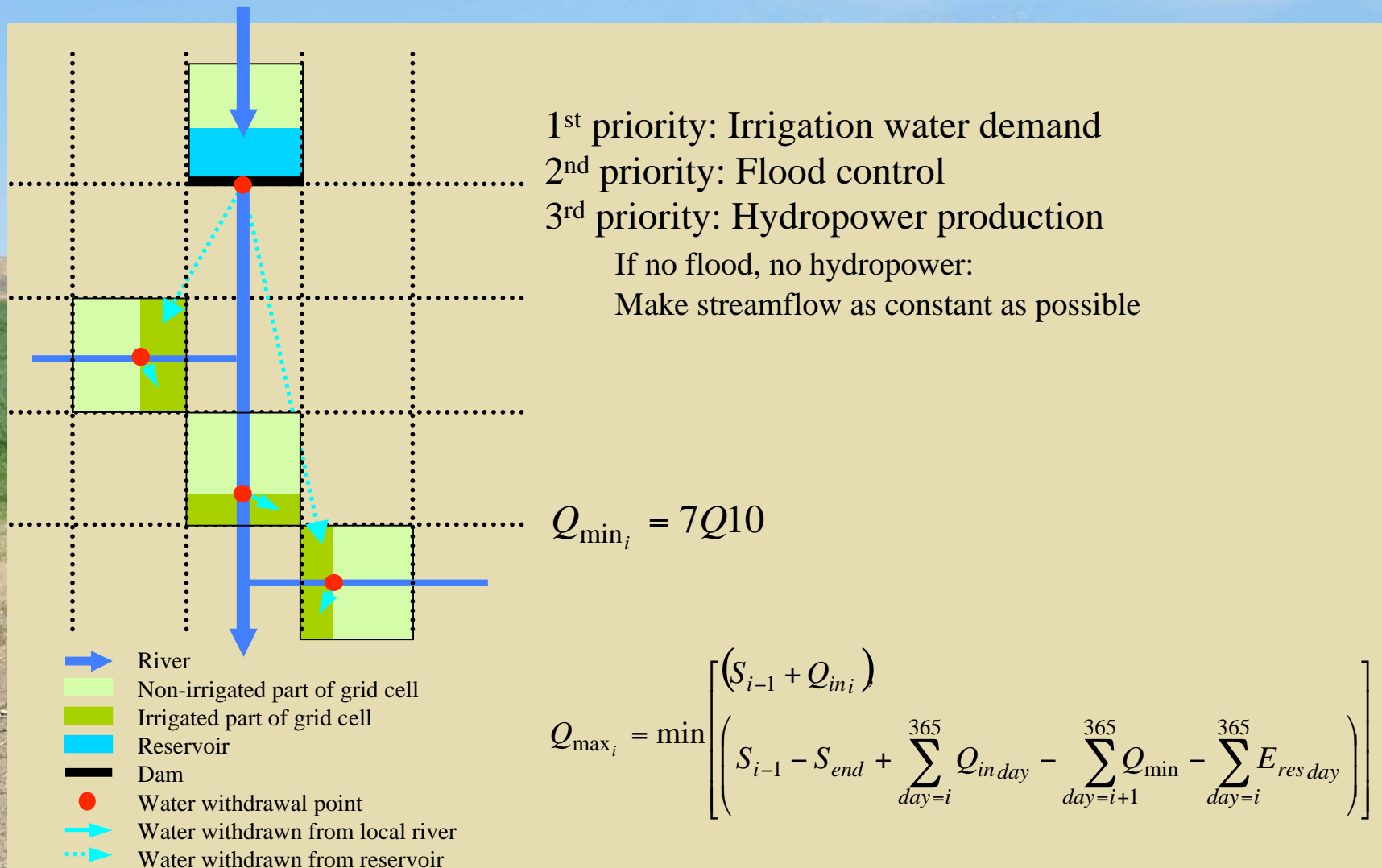
Time

Model development: Irrigation scheme

$$ET = K_c * ET_o$$

ET_o: Reference crop evapotranspiration

Model development: Reservoir model
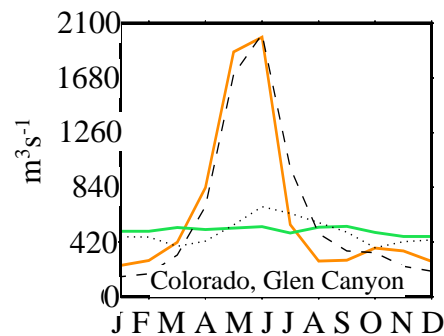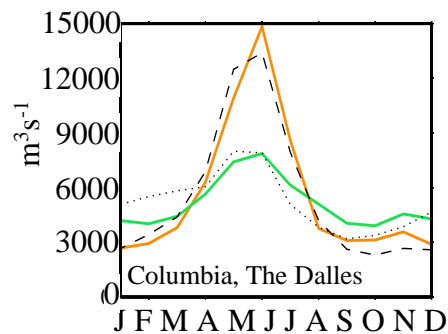

1st priority: Irrigation water demand
2nd priority: Flood control
3rd priority: Hydropower production

    If no flood, no hydropower:
    Make streamflow as constant as possible

Legend:
- → River
- ▢ Non-irrigated part of grid cell
- ▢ Irrigated part of grid cell
- ▢ Reservoir
- ▬ Dam
- ● Water withdrawal point
- → Water withdrawn from local river
- ⇢ Water withdrawn from reservoir

$$Q_{\min_i} = 7Q10$$

$$Q_{\max_i} = \min \left[\begin{array}{c} \left(S_{i-1} + Q_{in_i} \right) \\ \left(S_{i-1} - S_{end} + \sum_{day=i}^{365} Q_{in\,day} - \sum_{day=i+1}^{365} Q_{\min} - \sum_{day=i}^{365} E_{res\,day} \right) \end{array} \right]$$

Model development: Evaluation

Model evaluation:
1) Columbia, 2) Colorado,
and 3) Missouri River basins

- - - Naturalized streamflow
— Simulated, no reservoirs,
no irrigation
······ Observed streamflow
— Simulated, reservoirs
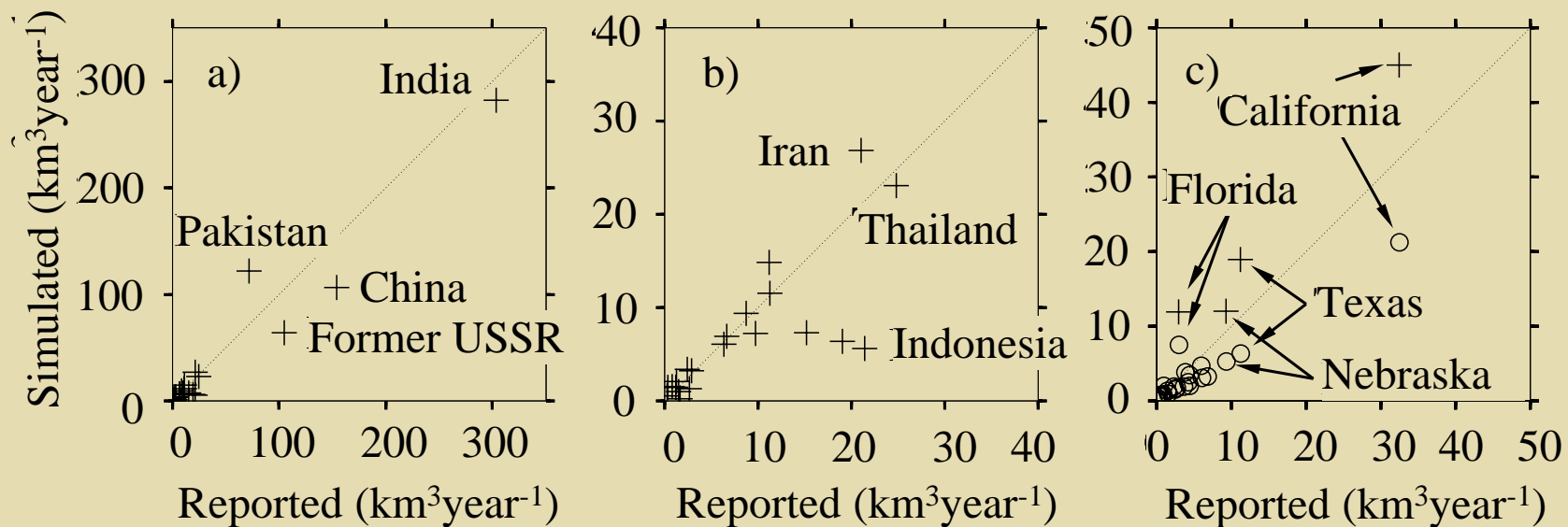and irrigation
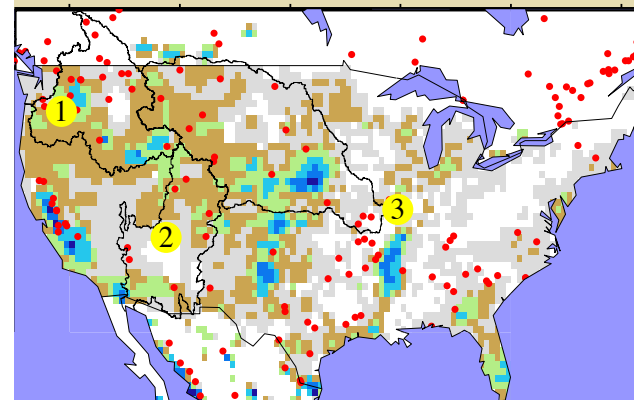
Percent irrigated areas

>50
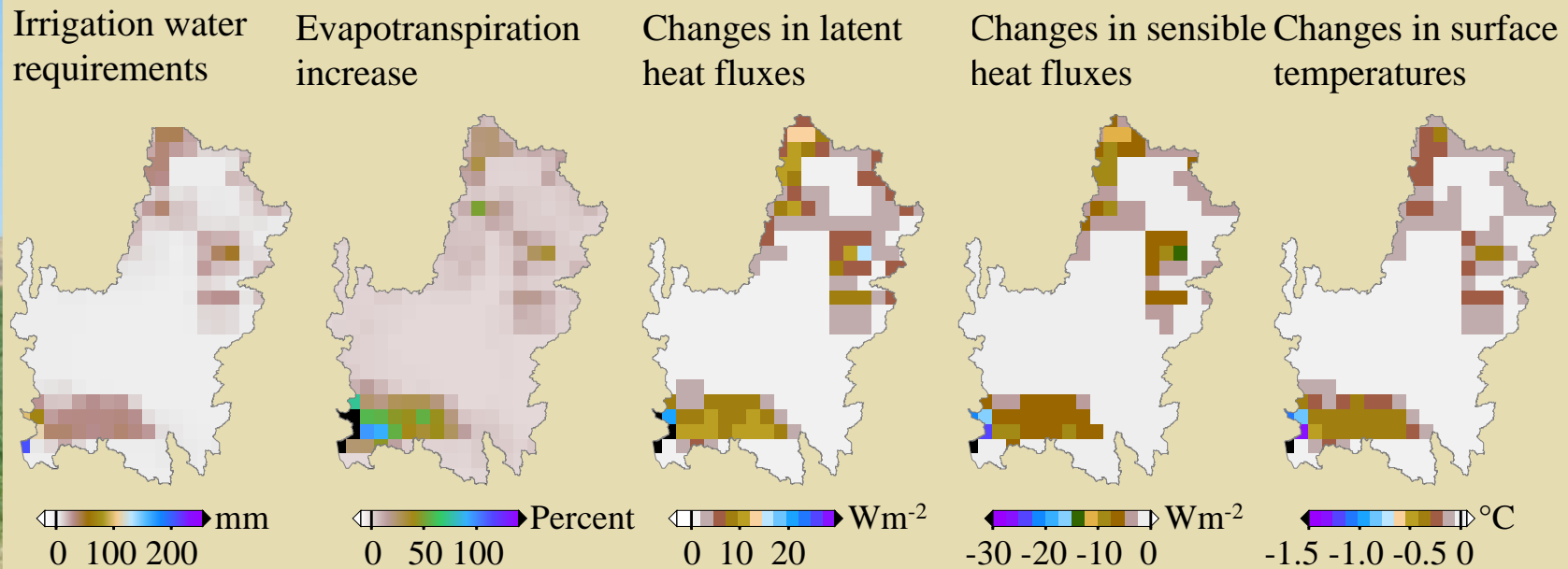30-50
15-30
5-15
1-5
0.1-1
<1

● Dam

Model development: Evaluation

a) Mean annual simulated and reported irrigation water requirements for countries in Asia. b) The lower values shown in b). c) Mean annual simulated irrigation water requirements (+) and simulated irrigation water use (o) compared to reported irrigation water use in the USA.

Colorado River basin

Irrigation water requirements	Evapotranspiration increase	Changes in latent heat fluxes	Changes in sensible heat fluxes	Changes in surface temperatures

mm 0 100 200   Percent 0 50 100   Wm^{-2} 0 10 20   Wm^{-2} -30 -20 -10 0   °C -1.5 -1.0 -0.5 0

- Figure: Results for three peak irrigation months (jun, jul, aug), averaged over the 20-year simulation period.
- Max changes in one cell during the summer: Evapotranspiration increases from 24 to 231 mm, latent heat decreases by 63 W m^{-2}, and daily averaged surface temperature decreases 2.1 °C
- Mean annual "natural" runoff and evapotranspiration: 42.3 and 335 mm
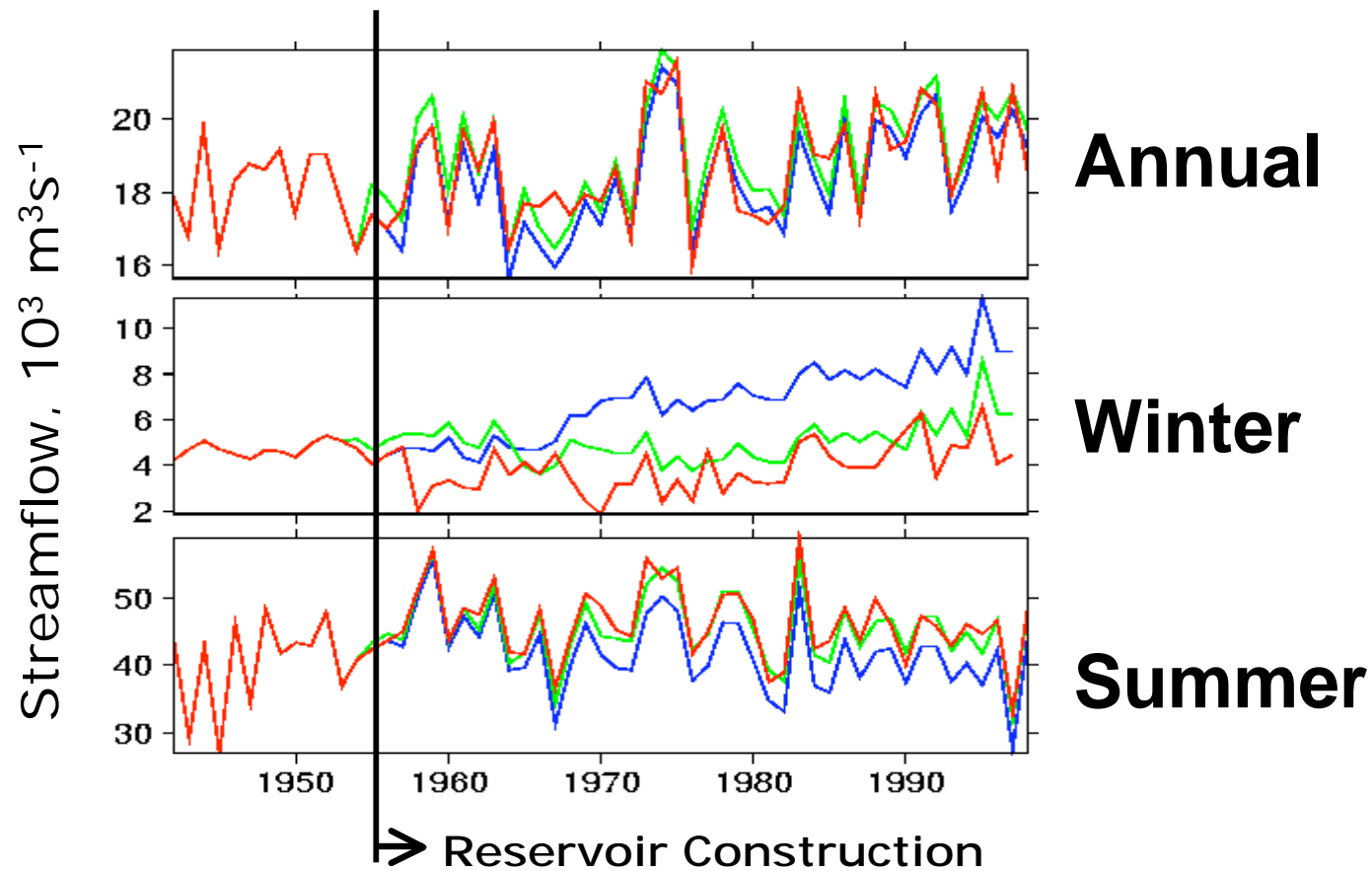- Mean annual "irrigated" runoff and evapotranspiration: 26.5 and 350 mm

Major Arctic Reservoirs (Capacity>1 km^3)

- **Lena:**
  - 7% Annual Q
- **Yenisei:**
  - 71% Annual Q
- **Ob':**
  - 16% Annual Q
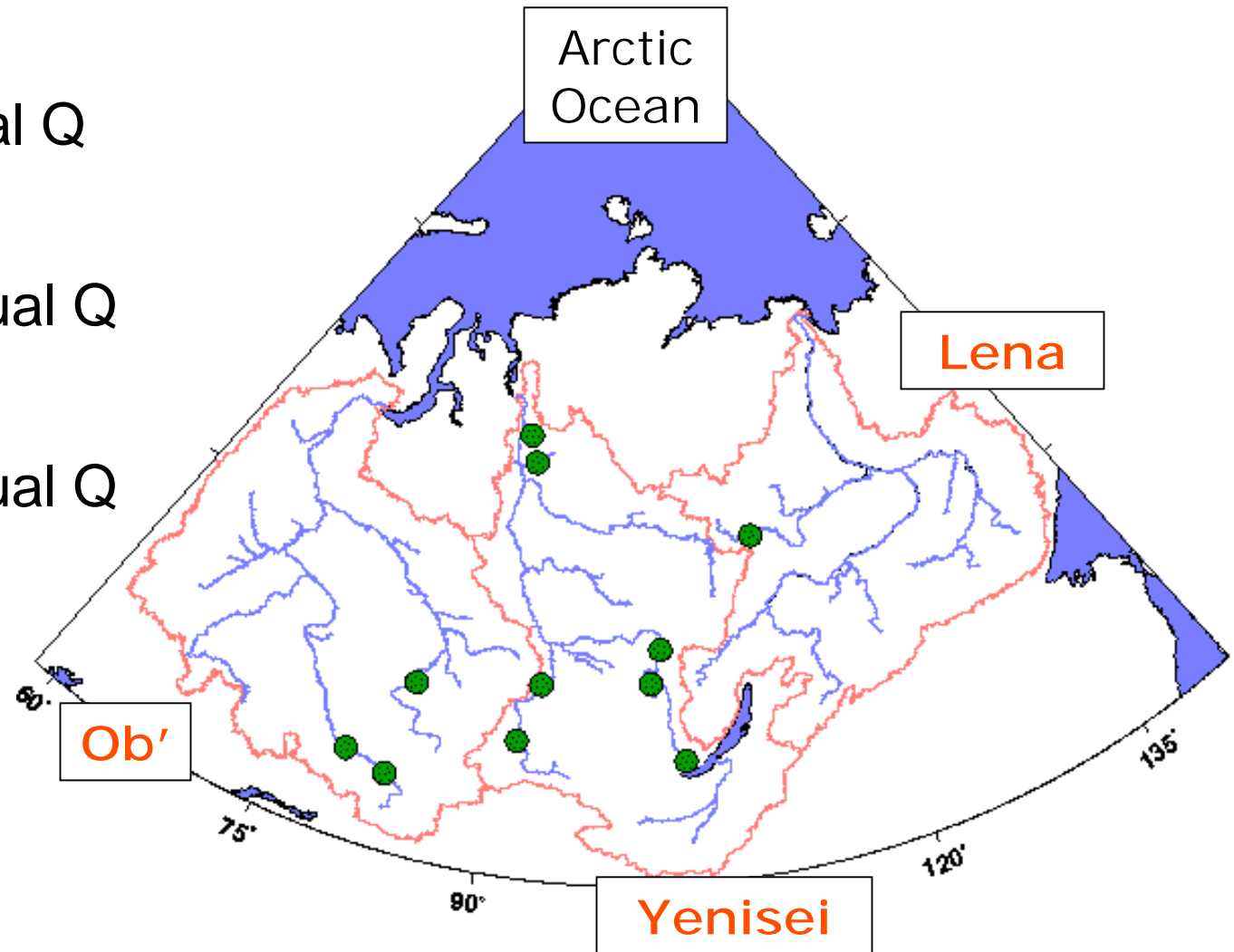
Streamflow Data (example: Lena)

The role of observations

- What do we know about the dynamics of surface water storage globally (in lakes, wetlands, river channels, and man-made reservoirs)?

- Clearly, the answer is "very little" – as compared with global river discharge data (deficient that they are due to lags in reporting and archiving, e.g., at GRDC, and decline in station networks), the global network for surface storage is essentially nil – presenting major scientific, and practical issues (e.g., for management of transboundary rivers)
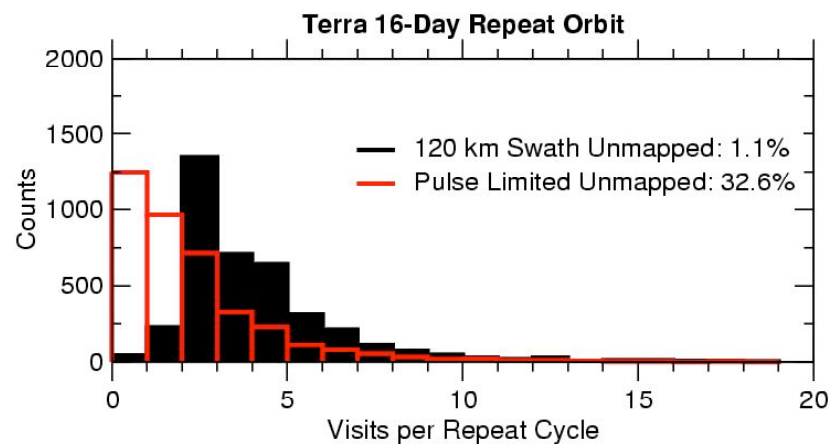
Location of global lakes and reservoirs for which stage data are currently available from Topex-Poseidon, Jason, and other altimeters
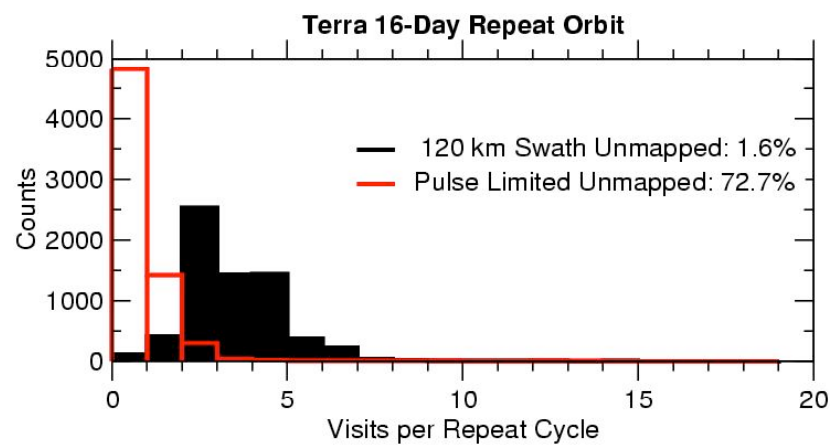

Map of lakes and reservoirs in «Hydroweb»

● Lakes ○ Reservoirs

Source: CNES (www.legos.obs-mip.fr/soa/hydrologie/hydroweb/)
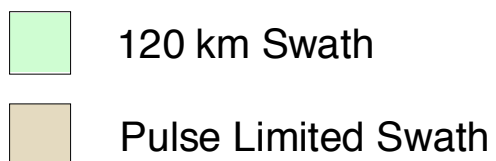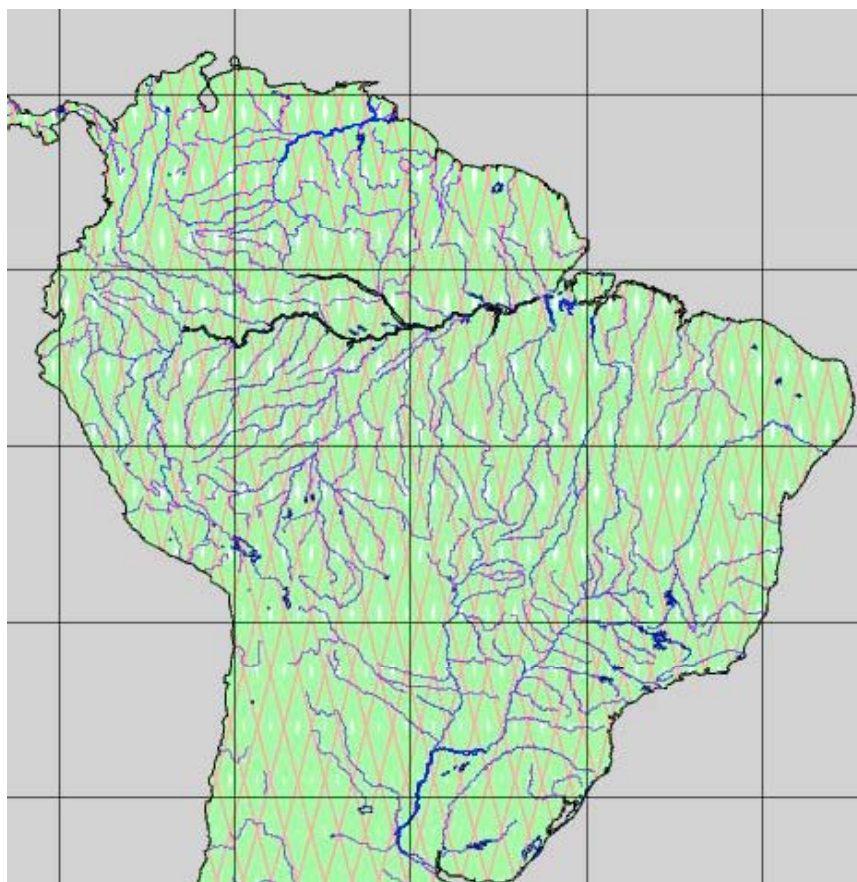
Global River Coverage Histogram
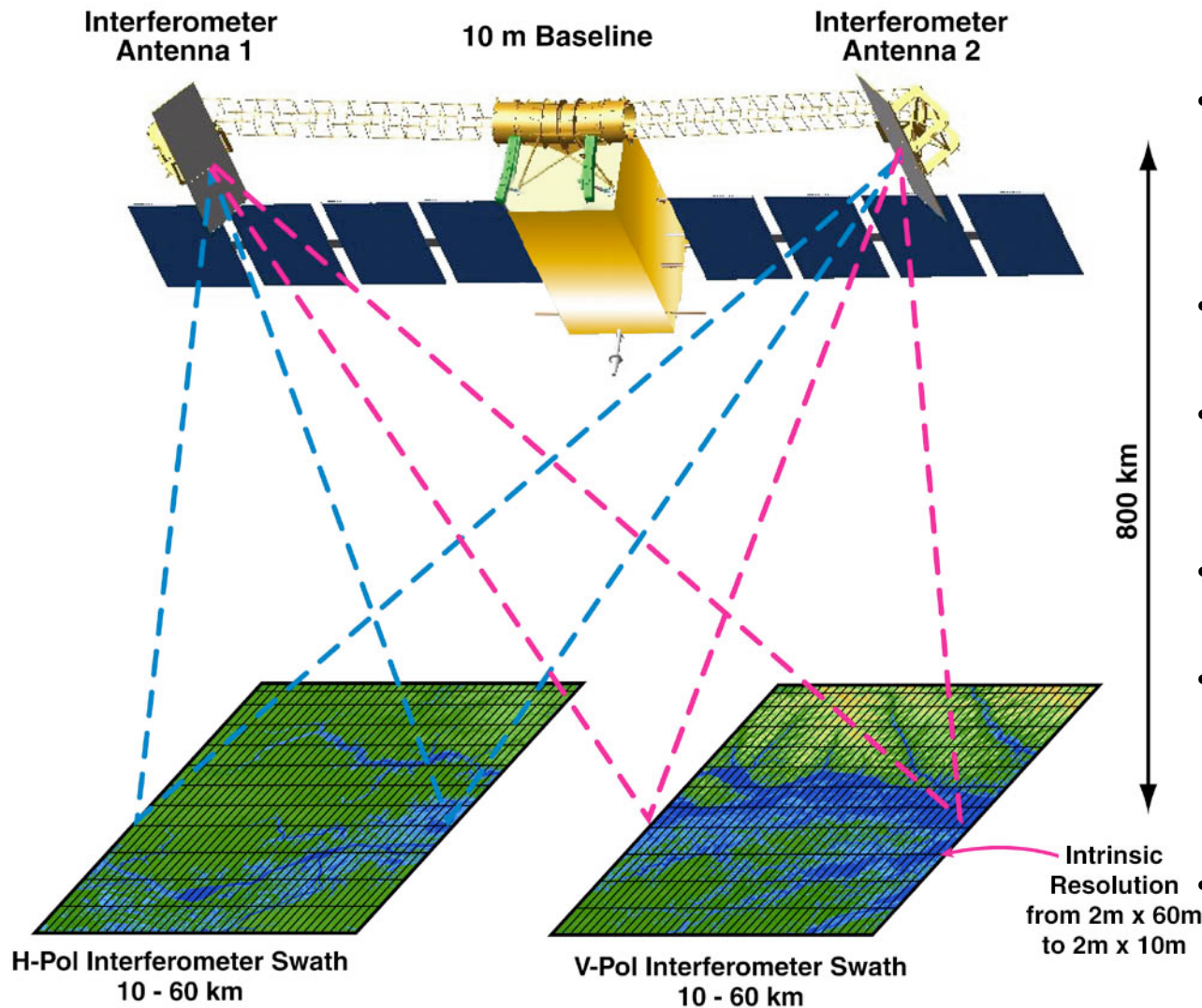
Global Lake Coverage Histogram

Visual courtesy Ernesto Rodriguez, JPL

KaRIN: Ka-Band Radar Intererometer

Interferometer Antenna 1

10 m Baseline

Interferometer Antenna 2

800 km

H-Pol Interferometer Swath 10 - 60 km

V-Pol Interferometer Swath 10 - 60 km

Intrinsic Resolution from 2m x 60m to 2m x 10m

- Ka-band SAR interferometric system with 2 swaths, 50 km each
- WSOA and SRTM heritage
- Produces heights and co-registered all-weather imagery
- 200 MHz bandwidth (0.75 cm range resolution)
- Use near-nadir returns for SAR altimeter/angle of arrival mode (e.g. Cryosat SIRAL mode) to fill swath
- No data compression onboard: data downlinked to NOAA Ka-band ground stations

These water elevation measurements are entirely new, especially on a global basis, and thus represent an incredible step forward in oceanography and hydrology.

Conclusions

- Global change will be the defining challenge faced by hydrologists in the 21st Century – prediction of the effects of land cover, climate, and water management on the land surface hydrological cycle

- Modeling approaches that address these challenges, especially at large scales where site-specific data are not available, are in their infancy

- The motivation for addressing these problems are both scientific and societal

- New observations will be critical to better understanding the dynamics of water storage and movement at the land surface